INVESTIGATION ON SHIELDED METAL ARC WELDING OF ARMOUR PLATE WITH VARIOUS ELECTRODES FOR DEFENCE APPLICATION

A SYNOPSIS

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1. INTRODUCTION

The combat vehicle in emerging defence applications plays an essential role all over the world. It is used to attack the enemies in a combat environment through missiles and ammunition. The combat vehicle/armour vehicle has significant parts such as the wheel, body structure, and missile system. Different armour thicknesses are used to enhance the hardenability in different components of the combat vehicle. The different weight percentages of alloying elements are used to prepare the different grades of armour plates and each plate is converted into different thicknesses from 2.5 to 150 mm. The carbon content and stiffness concerning thickness can withstand high flow stress in armour steels. The formation of martensite structure produces a high strength in steels with the help of the heat treatment process and can withstand the dynamic loads in armour steels. The martensite conversion is obtained by internal stresses related to the heat treatment of Quenching (Q) and Tempering (T) processes. Heat treatment of 900 ◦C in the 'Q' process helps to maintain the capacity of retained austenite and enhance the hardness property. Heat treatment of 200 ◦C in the 'T' process helps to keep the capacity of martensite lath and enhance the impact of toughness.

Combat vehicles are manufactured using armour steel plates of heavy thickness. It plays a crucial role in saving the soldiers from the enemy's missiles, and weld joint (joining of armour plate with electrode by heat source) reduces the vehicle weight rather than other joints. Reducing the size and weight is a major issue in armour vehicles manufactured without affecting the ballistic protection. The armour steel plates obtain the required dimensions by the machined and welding process used to produce the structural components in the combat vehicle. Armour welding has difficulty forming a better joint because of the high carbon content (carbon equivalent) and hydrogen content involved in the welding of armour steel plates. A preheat and post-heat treatment helps create a suitable composition in the weld zone at which Hydrogen Induced Cracking (HIC) is controlled. The weld groove plays a vital role in the arc welding process, and it is widely used in the conventional welding process.

The welding of armour grade steel is compared with different processes, such as cold metal transfer (CMT), gas metal arc welding (GMAW), and hybrid plasma arc welding processes (HPAW). However, SMAW is commonly used for joining of thick steel sections due to less cost and easy availability of the equipment. Austenitic

stainless steel (ASS) welding consumable (electrode) is commonly used for SMAW of quenched and tempered steels to prevent hydrogen induced cracking (HIC), as they have higher solubility for hydrogen in austenitic phase.

In this study, an attempt is made to investigate the SMAW welding of 20 mm armour plate by single bevel surface modification. In this welding, different electrodes are used to investigate the weld characteristics of the 20 mm thickness of armour weldment. The mechanical property and the microstructural characterization of the welded plates are analyzed. The process that produces lower HAZ, higher hardness, tensile strength and impact strength are finally identify the better weldability. Additionally, optical, SEM microstructures are discussed with different armour weldments. The fracture surfaces of tensile and impact weldments also discussed. These properties of armour weldment are analyzed and it is conforming to satisfy the requirements of compact environment.

2. LITERATURE REVIEW

Literature survey was done on the armour steel, welding process in armour weldment, electrodes and welding parameters, weld groove in armour weldment, microstructure on armour weldment, and fracture studies on armour weldment.

Lenihan et al. [1] exhibits that Armoured Fighting Vehicle (AFV) is a military vehicle with a hull specifically designed to resist penetration from enemy weapons, thus allowing it to move more freely in the battlespace. Senthil and Iqbal [2] was investigated that ballistic performance in the armour plate. In the present study, projectile is tested with different oblique angles in armour steel plate. The armour steel proved that good ballistic performance. As a result of dynamic loads, cracks created in the fusion line can very easily propagate along this zone, which can lead to catastrophic failure. Cabrilo and Geric [3] reported that hardness value is exceeded up to 521 HV in CGHAZ, it is critical to creating a crack in the weld zone as per MIL-STD-1185. The HV value in the CGHAZ is limited from 390 HV to 420 HV.

Arifin [4] was studied the microstructure, destructive test (tensile, impact, and hardness test) and non- destructive test ((Magnetic particle, radiography, ultrasonic test)) of armour weldments with different arc welding processes namely Shielded Metal Arc Welding (SMAW), submerged arc welding (SAW), gas arc welding (GMAW), tungsten arc welding (GTAW) and others. The SMAW is usually used in industry due

to easy and simple equipment. The SMAW enhance the weld quality. Magudeeswaran et al. [5] reported that defect free weld joint is obtained in armour weldment for combat vehicle by Flux Cored Arc Welding (FCAW) process. Fei et al. [6] exhibits that SMAW process with ASS (ASS E307) consumables to eliminate hydrogen induced cracking (HIC) in the armour weldment. The suitable composition of ASS electrode has mechanical and ballistic properties in the armour weld joint. Balaguru et al. [7] reported that SMAW is the typical joining method for high-strength parts. It is reducing the weld defects and easy to weld the high strength materials.

Pathak et al. [8] exhibits that ultimate tensile strength of single bevel groove joint (906 Mpa) higher than single V groove Joint (865 Mpa). The reduction of heat input: Narrow HAZ with a small reduction in its hardness values. High reduction in the width of fusion zone microstructure. Morsy et al. [9] proved that ballistic resistance of HAZ is achieved by heat input of 1.29 kJ/mm in the GMAW process as compared to 1.55 kJ/mm. The higher heat input is increasing the cooling time at the weld zone. Savic and Cabrilo [10] investigated that result of the ballistic test was confirmed by crack length, which satisfied the impact velocity, as required by the standard. The GMAW with armour grade electrode (AWS A5.10, MIL-100s) is to meet the ballistic requirements. Kim and Yi [11] exhibits that single-bevel groove with FCAW has good mechanical property in 30 mm thickness of steel plate. Maudeeswaran et al. [12] reported that single bevel grove reduces the number of passes/ electrodes in the weld line as compared to ‘V’ groove joint.

Van et al. [13] investigated that composition of electrode is related with mechanical properties and mechanical properties of weld zone is related with microstructure of the armour weldment. Souza et al. [14] exhibits that ASS weldment is successfully obtained martensite structure in HAZ of the armour weldment. ASS electrode is Low thermal conductivity. Morsy et al. [15] observed that the SMAW joint welded using ASS consumable (having higher Cr_{eq}/Ni_{eq} ratio) exhibited superior tensile properties as result of the evolution of ferrite phase with vermicular and globular morphology in the austenite matrix at weld metal region. Balaguru et al. [16] reported that SMAW with ASS electrode is used to weld the armour steel. The chemical composition of electrode contains higher percentage of nickel. It is presented in the fusion zone by welding time which gives higher fracture toughness in the armour weldment.

Saxena et al. [17] exhibits that defect free weld joint is obtained by Flux Cored Arc Welding (FCAW) process. Avoid hydrogen induced cracking (HIC) in the armour weldment. Magudeeswaran et al. [18] investigated that 500 HBW armour steel and ER110 welding wires are welded by using GMAW process. The study indicated that, welding parameters should be optimized to prevent the hardness decrement for the welding process. Yildizhan and Aykilic [19] reported that armor steel welded joints are expected to have a tensile strength not lower than 550 MPa, in order to satisfy the requirements of MIL-STD-1185.

Cabrilo and Geric [20] proved that fracture studies are the ability to measure the withstanding force of armour steel. The impact strength of armour steel has sufficient energy in compact environment. Choudhary et al. [21] investigated that Mil-A 46100 Armour plate welded with GMAW process by using ASS electrode. Fractures in the armour steel welded joints may exhibit brittle or ductile characteristics depending on the groove types, carbon ratio in the compounds, and weld electrode used in the welding operations. In the overall scheme of Charpy tests conducted on the samples chosen, the cleavage in the welded joint is very quick and mostly brittle owing to the carbon ratio in the weld wires' compounds. Ozdemir [22] is reported that GMAW with ASS electrode is used to weld the armour plate and it is obtaining the good fracture toughness. Cabrilo et al. [23] reported that fusion zone and HAZ have significantly higher fracture toughness than armour steel, providing safe welded joints in respect to brittle fracture.

In this study, an attempt is made to investigate the armour weld and this surface modification of weld-groove is prepared by Water Jet (WJ) process. The armour plates are welded by the SMAW process with suitable welding parameters. The mechanical property and the microstructural characterization of the welded plates are analyzed. The process that produces lower HAZ, higher hardness, tensile strength and impact strength are finally identified to confirm better weldability.

3. RESEARCH PROBLEM

- The armour welding by electrode is not enhance the mechanical properties in the weld zone. In this reason, bullets are easily penetrated to armour steel plate.
- The welding parameters (pre heat / post heat) are influence the hydrogen induced cracking and HAZ in the weld zone.

- The different electrodes are influence the mechanical properties in the weld zone. From the literature survey, weldability of armour materials has been studied in Arc welding process. In that, the research related to welding with different electrode is rarely available.
- The welding of defensive material comprised of hardened martensitic microstructure. In any case, the over hardened HAZ has no genuine outcomes of martensitic microstructure by using ASS electrode and its more fragile in the fusion zone.
- Moreover, the influence of special grade of stainless steel and Military grade HSLA electrode in Welding also very rare. This is the seed for this proposed research work.

4. OBJECTIVE

- To control the Hydrogen Induced Cracking (HIC) and HAZ in the armour weldment by welding parameters.
- To reduce the width of the HAZ is complicated in the weld zone of the armour weldment.
- To enhance the mechanical properties in the weld zone by using different electrode in the armour weldment.
- To develop the genuine outcome of microstructure in the HAZ in the armour weldment by using welding parameter.
- The aim was to significantly improve the ballistic performance in the armour weldment (tensile strength, hardness, impact strength) on combat vehicles.

5. ORGANIZATION OF THESIS

Chapter 1: Introduction

In this chapter discussed about armour steel in defence applications, different welding processes in armour weldment, electrode and welding parameters, weld groove in armour weldment, microstructure on armour weldment, and fracture studies on armour weldment. The mechanical tests of hardness, tensile, impact is discussed and microstructure of armour weldments also discussed.

Chapter 2: Literature Review

A detailed literature survey provided on the recent research regarding various

issues including armour steel in defence applications, weldability of armour steel, pre/post heat treatment in armour weldment was described. The fusion zone of armour weldment is failed under ballistic performance, the heat input, weld groove of welding parameters influences the mechanical strength of the armour weldment mechanical properties, macrostructure of armour weldment in different welding process was described. Based on the literature review, it presented the research gap in this area. The objectives of this research work have been articulated as well.

Chapter 3: Materials and Experimental details

This chapter provides the research methodology used for this research work in Figure 1. The weld metal preparation, water jet machining process, different electrodes are selected under ASTM section II standard. The four different armour weldments by using different electrodes are discussed. Different electrodes of welding parameters, the destructive test (mechanical test) results of tensile, impact, hardness test and non-destructive test (NDT) results of radiography test is discussed under the ASTM standard.

The armour plate is prepared as per metallographic techniques and 1 kg of the load is applied to measure the micro-Vickers hardness (micro-HV) as per ASTM A370: 2018 standard. Three readings are taken from the above-mentioned material by micro-HV machine and average readings are taken to the final account. The hardness test is used to evaluate the weldability in weld armour plates as per metallographic techniques. The 10 kg of the load is applied to different armour weldment by using different electrodes and measure the HV values. Each weld specimen has 19 readings of HV and these readings are divided into two sections in this research, such as fusion zone (5 locations) and HAZ (14 locations). The HAZ is divided into three categories with different locations, namely CGHAZ (5 locations), FGHAZ (5 locations), and F-HAZ (4 locations). 19 readings are taken from armour weldment by HV machine as per ASME SEC IX 2019 standard. The average readings of HV values in each zone (fusion zone, CGHAZ, FGHAZ, F-HAZ) are taken into account.

The tensile test plays a major role in evaluating the weldability in the mechanical examination of weld armour plates. The universal Testing machine with a maximum loading capacity of 400 kN is used to find the tensile strength in the base material and weld armour plates at ambient temperature 25.2 ◦C. The Charpy impact test evaluates

the toughness property in the base metal and weld armour plates. The Charpy impact of the armour weldments are prepared as per ASME SEC IX 2019. The metallurgical test results of macrostructure, optical and SEM microstructure, grain size of armour steel and armour weldment is discussed.

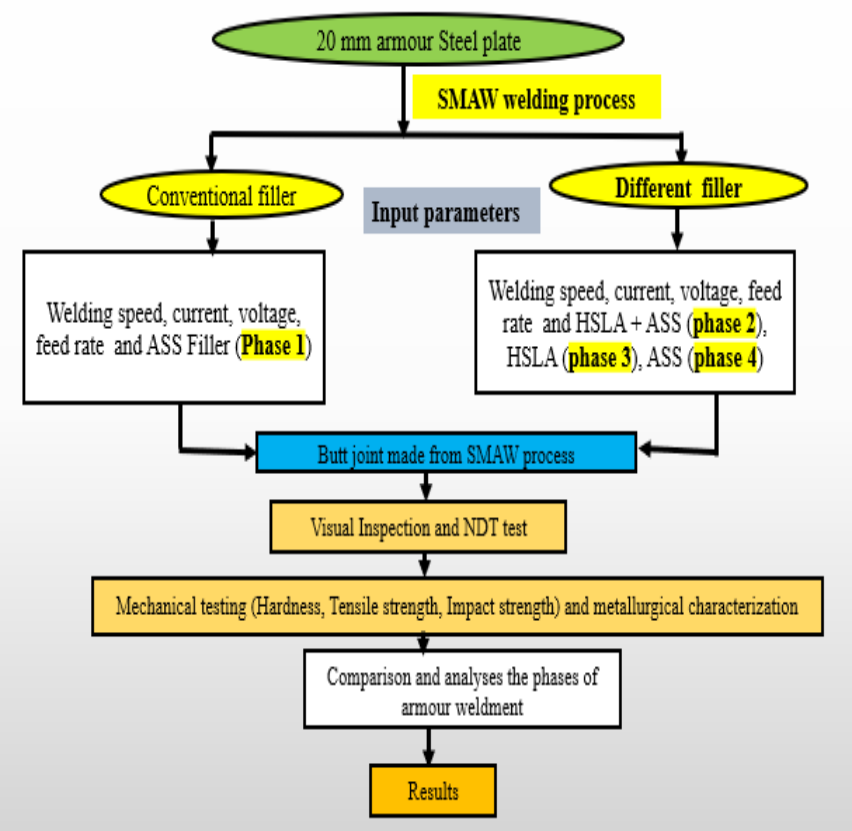
20 mm armour Steel plate
SMAW welding process
Conventional filler
Input parameters
Different filler
Welding speed, current, voltage, feed rate and ASS Filler (Phase 1)
Welding speed, current, voltage, feed rate and HSLA + ASS (phase 2), HSLA (phase 3), ASS (phase 4)
Butt joint made from SMAW process
Visual Inspection and NDT test
Mechanical testing (Hardness, Tensile strength, Impact strength) and metallurgical characterization
Comparison and analyses the phases of armour weldment
Results

Figure 1 Research Methodology

Chapter 4: Analysis of weldment 1

A composition of Austenitic Stainless Steel (ASS) electrode is used to weld the 20 mm thickness of armour steel by using SMAW process. This weld has 11 passes to prepare the weld joint as shown in Figure 2 and the process is called as weldment 1. The macrostructure of width of the HAZ in armour weldment 1 is accepted in the range as per MIL-STAN-1185 in defence applications as shown in Figure 3. In this study, macrostructure, optical microstructures, SEM microstructures with EDAX results was analysed. These hardness, tensile, impact test results of mechanical properties are obtained in the weldment 1. These mechanical results (hardness, tensile strength, impact strength) were significantly enhancing the ballistic performance of the armour weldment.

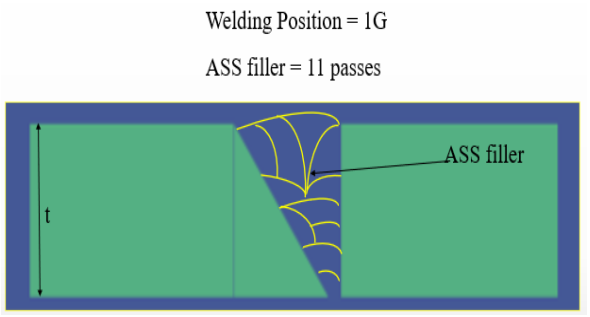

Figure 2 Number of passes in weldment 1

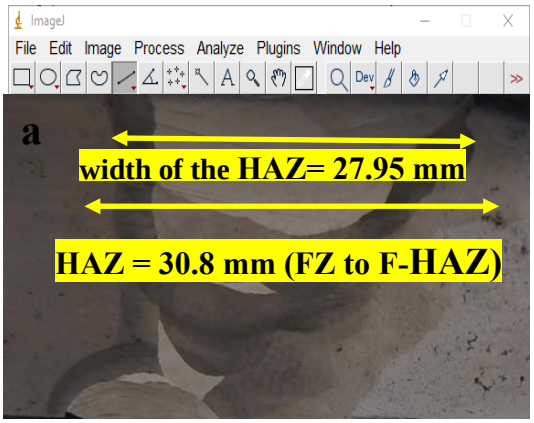

Figure 3 Macrostructure of width of the HAZ in weldment 1.

Chapter 5: Analysis of weldment 2

A composition of High Strength Low Alloy (HSLA) electrode with Austenitic Stainless Steel (ASS) electrode is used to weld the 20 mm thickness of armour steel by using SMAW process. This weld has 13 passes to prepare the weld joint as shown in Figure 4 and the process is called as weldment 2. The macrostructure of width of the HAZ in armour weldment 2 is accepted in the range as per MIL-STAN-1185 as shown in Figure 5. In this study, macrostructure, optical microstructures, SEM microstructures with EDAX results was analysed. These hardness, tensile, impact test results of mechanical properties are obtained in the weldment 2.

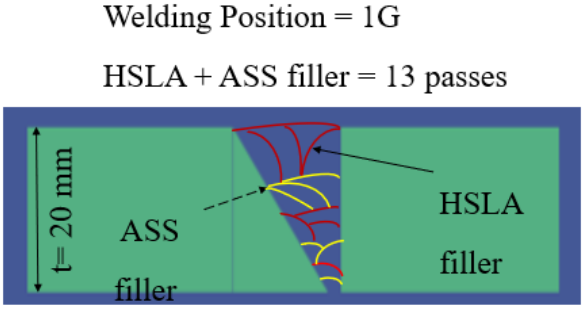

Figure 4 Number of passes in weldment 2

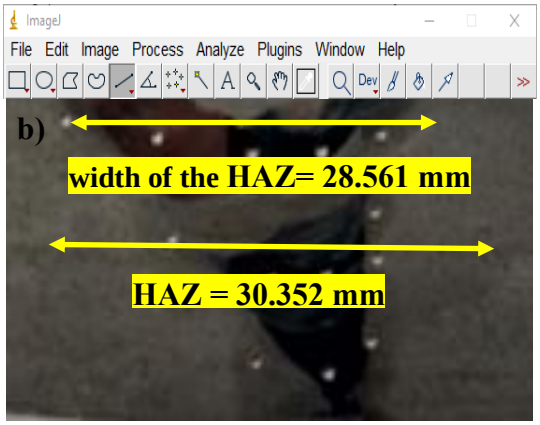

Figure 5 Macrostructure of width of the HAZ in weldment 2.

Chapter 6: Analysis of weldment 3

A composition of High Strength Low Alloy (HSLA) electrode is used to weld the 20 mm thickness of armour steel by using SMAW process. This weld has 12 passes to prepare the weld joint as shown in Figure 6 and the process is called as weldment 3. The macrostructure of width of the HAZ in armour weldment 2 is accepted in the range as per MIL-STAN-1185 as shown in Figure 7. In this study, macrostructure, optical microstructures, SEM microstructures with EDAX results was analysed. These hardness, tensile, impact test results of mechanical properties are obtained in the weldment 3.

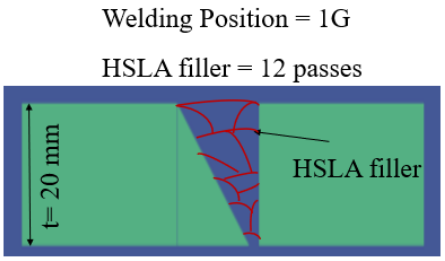

Figure 6 Number of passes in weldment 3

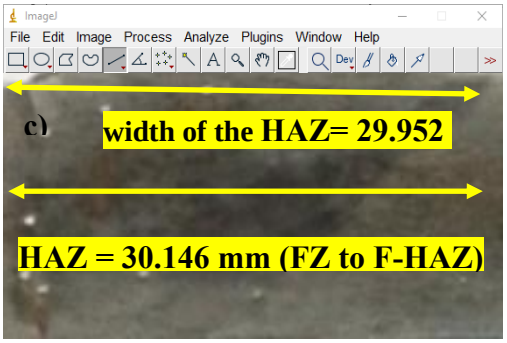

Figure 7 Macrostructure of width of the HAZ in weldment 3.

Chapter 7: Analysis of weldment 4

A composition of ASS electrode is used to weld the 20 mm thickness of armour steel by using SMAW process. This weld has 17 passes to prepare the weld joint as shown in Figure 8 and the process is called as weldment 4. The macrostructure of width of the HAZ in armour weldment 2 is accepted in the range as per MIL-STAN-1185 as shown in Figure 9. In this study, macrostructure, optical microstructures, SEM microstructures with EDAX results was analysed. These hardness, tensile, impact test results of mechanical properties are obtained in the weldment 4.

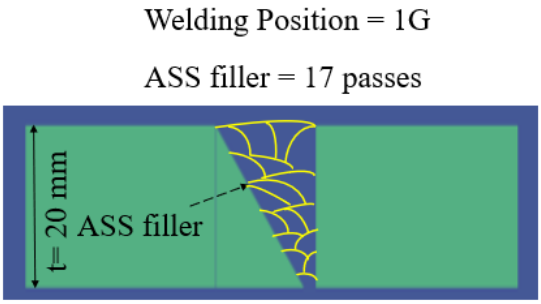

Figure 8 Number of passes in weldment 4 (ASS)

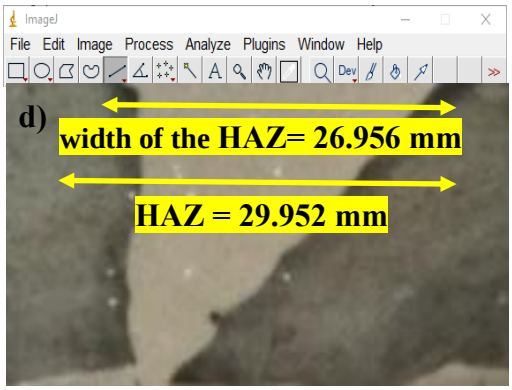

Figure 9 Macrostructure of width of the HAZ in weldment 4.

The tensile strength of base metal is higher than four weldments but tensile properties of weldment 2, weldment 3, and weldment 4 is satisfying the ballistic performance of combat vehicle. The tensile failure of weldment 2, weldment 3, and weldment 4 is failed in base metal. The hardness value is playing an important role in armour application. Comparision of different armour weldments as shown in Figure 10. These tensile and impact values of different armour weldment is to meet the MIL-STD-1185.

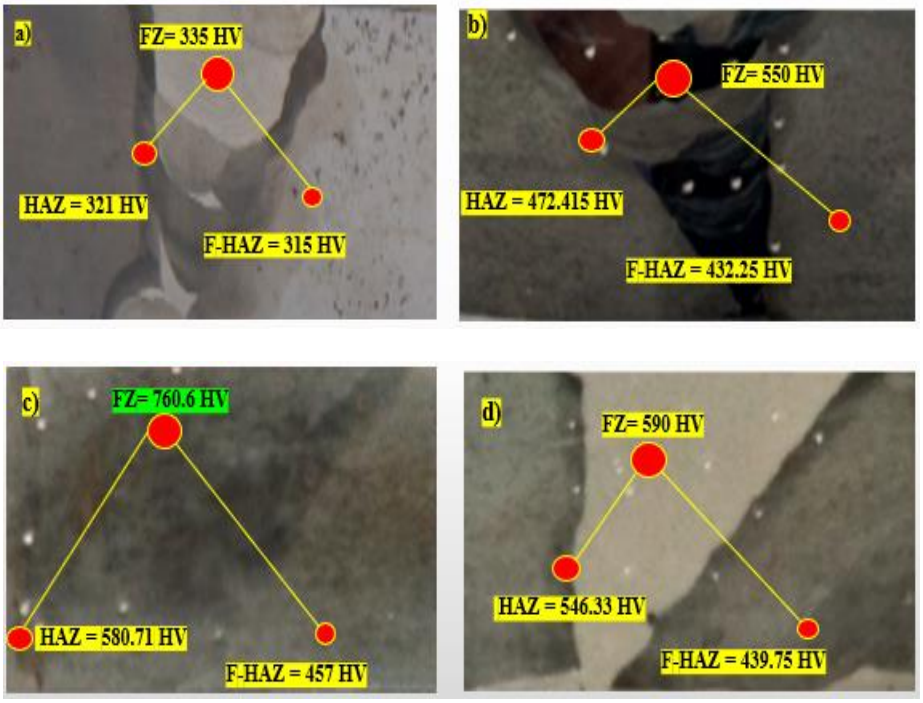

Figure 10 The average value of Vickers hardness: (a) weldment 1, (b) weldment 2, (c) weldment 3, (d) weldment 4.

The weldment 2, weldment 3, and weldment 4 mechanical properties of FZ, HAZ has higher values as compared to armour steel plate. The microstructure results also obtained the desired structures. The defect free weld joint is confirmed by radiography test as shown in Figure 11.

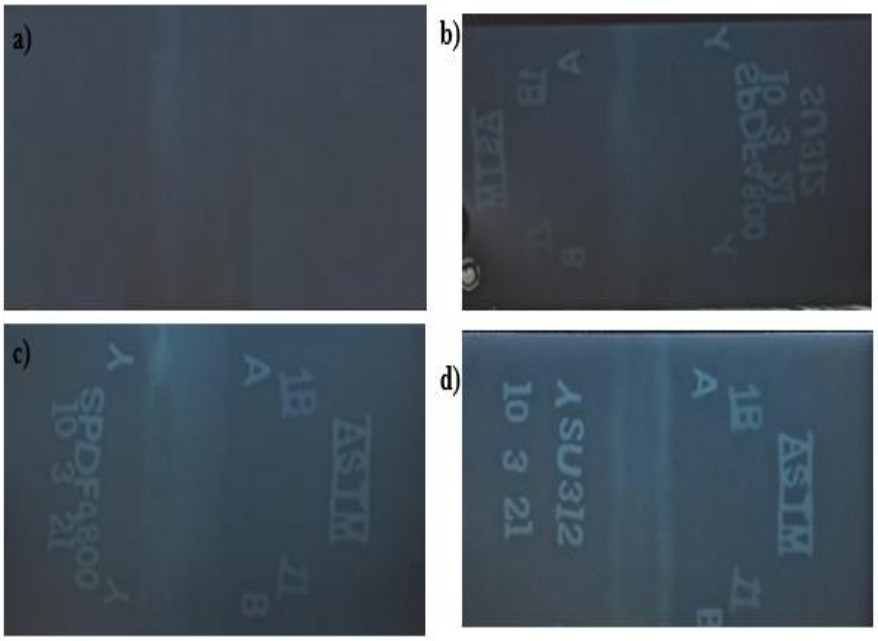

Figure 11 Radiography test results

Chapter 8: Discussion on weldments

The macrostructure, microstructure of armour plate, different passes of armour weldment is discussed. Machining surface of weld sample preparation. The different electrodes are used in the armour weldment and called as weldment 1, weldment 2, weldment 3, and weldment 4. These High Strength Low Alloy HSLA electrode, different composition of Austenitic Stainless Steel (ASS) electrode is used to prepare the four different weldments by using SMAW process. The macrostructure of width of the HAZ in different armour weldment is accepted in the range as per MIL-STAN-1185 in defence applications.

The optical microstructure of the asymmetric joining of the fusion zone and HAZ illustrates the vertical schematic drawing in the armour weldment. The fusion zone of the armour weldment consists of delta ferrite and retained austenite structure. The fusion zone and HAZ in the base material have different mechanical properties due to increase in heat, and slow cooling (1 ^{o}C/s) has occurred in the welding environment.

The 5 % delta ferrite on the fusion zone was evaluated and it's based on the weight percentage of Cr (20.6 %) and Ni (13.8 %) equivalents in ASS electrode, as shown in Fig.6. A 5 - 10 % delta ferrite is an acceptable range of fusion zone in the armour weldment by Schaeffler diagram and it enhance the impact properties. The horizontal line is called as dendritic arms perpendicular to the weld interface (primary dendritic arms (PDA)). The vertical line is called as dendritic arms parallel to the weld interface (secondary dendritic arms (SDA)). As these lines increase, the failure occurs easily at normal tensile load conditions. The fusion zone has a good ductile property due to the ASS electrode with suitable welding parameters. The microstructure of armour weldment creates a suitable microstructure in the fusion zone and a martensite structure in the heat affected zone, which is stronger than any other steel grade. The weldment 2, weldment 3, and weldment 4 are investigated and fusion zone results are varied concerning different composition of electrodes. The weldment 1 was obtained the delta ferrite + austenite microstructure in the fusion zone (FZ), weldment 2 has ferrite + austenite, martensite microstructure in the FZ, and weldment 3 has martensite + retained austenite microstructure in the FZ. Additionally, weldment 4 was obtained the ferrite + austenite matrix.

The base metal pre heated upto 200 °C for 10 minutes and 4 weldments of

electrodes are pre heated upto 200 °C for 1 hour time duration. It is helps to reduces the HIC. The post weld heat treatment is applied to 4 weldments at 200 °C for 30 minutes time duration to reduces the hardness and increase the toughness properties. Pre/Post heat treatment is playing an important role in armour weldment.

The mechanical properties of weldment 2 (Hybrid electrode) were obtained sufficient hardness in the HAZ. This hardness is to meet the military requirement under dynamic loading condition as per MIL-STD-1185. The weldment 2, weldment 3, and weldment 4 was slightly increase the hardness in fusion zone as compared to the hardness in the weldment 1. The Comparision on tensile and impact values of base metal, and different armour weldment is shown in Table 1.

Table 1. Tensile and Impact properties of base metal and weld metal

Specimens	Load at yield (KN)	Yield stress (N/mm^2)	Load at peak (KN)	Tensile strength (N/mm^2)	Reduction Area (%)	Elongation (%)	Joint Efficiency (%)	Impact strength (J)
20 mm armour	244.76	948.482	270.620	1048.694	31.73	22.52	-	14
Phase 1 filler	-	-	-	588.399	-	38	-	-
Phase 1 weld	27.1	435.612	33.2	533.665	11.77	4.38	46	108
Phase 2 weld	175.40	484.390	206.800	590.105	24.64	33.42	51	48
Phase 3 filler				781.06		22.05		
Phase 3 weld	166.02	459.89	212.02	587.314	28.83	58.48	49	114
Phase 4 filler				752		27.8		
Phase 4 weld	116.72	335.61	214.720	617.396	36	63.820	35	64

Chapter 9: Conclusion

In this investigation, the Welding attributes of armour steel in shielded metal arc welding for defence application was analysed. In the combat environment, accessibility of SMAW process is a suitable welding process of armour weldment in defence vehicle structures.

A single bevel weld-groove is used and obtained genuine outcomes of reduce the width of the HAZ, balancing the half percentage of base material in the FZ as compared to V groove. The welding parameters of Pre/Post heat treatment is proved that control the Hydrogen Induced Cracking (HIC) and remove the residual stresses at which defect free weld joint is obtained in armour weldment and perform the ballistic resistance in the combat environment. The Radiography test (non-destructive test) is exhibiting that defect free weld joint is obtained in 4 weldments of electrodes by using

SAMW process. The macrostructure of four armour weldment was proved that width of the HAZ is obtained in desired value as per MIL-STD-1185. The microstructures on different weldments of HAZ in the OM, SEM results were obtained genuine outcome in four different armour weldments. The weldment 1 weldment is not satisfying the ballistic performance and tensile failure is occurred in fusion zone of the armour weldment.

The Hardness, impact strength in the fusion zone, HAZ of weldment 2, weldment 3, and weldment 4 is achieved as higher value than armour steel. The tensile strength of four different armour weldment has lower value as compared to armour steel. The mechanical examination of Hardness, Tensile, and Impact (Destructive test) strength in the fusion zone results are meet the military requirements as per MIL-STD-1185. The tensile failure of weldment 2, weldment 3, and weldment 4 weldment is failed in base metal (apart from weld zone) of the test sample.

The mechanical properties of weldment 2 weldment (Hybrid electrode) were obtained sufficient hardness in the HAZ. This hardness is to meet the military requirement under dynamic loading condition as per MIL-STD-1185. The p weldment 3 and weldment 4 weldment was obtained slightly increase the hardness as compared to HAZ hardness in the weldment 2 weldment. In this result, armour weldment satisfies the width of the HAZ, genuine outcome of HAZ microstructure, higher hardness, tensile strength and impact strength are finally identified to confirm better weldability of armor steel by using the SMAW process. These results (weldment 2, weldment 3, and weldment 4) are meet the ballistic performance and satisfy the combat vehicle requirements as per MIL-STD-1185.

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